THORIUM CYCLE IMPLEMENTATION THROUGH PLUTONIUM INCINERATION BY THORIUM MOLTEN-SALT NUCLEAR ENERGY SYNERGETICS*

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Abstract. Considering the increasing world energy demand and the urgent necessity of replacement of fossil-fuel by nuclear energy for survival of the global environmental crisis, we urgently need to prepare a more rational and a huge nuclear industry. As an improved alternative of present technology, the utilization of U is strongly recommended. ORNL proposed an idealistic MSBR since 1970. We modified it to the world-wide applicable system: THORIMS-NES [Thorium Molten-Salt Nuclear Energy Synergetic System], which is composed of simple thermal fission power stations (FUJI) and fissile-producing Accelerator Molten-Salt Breeder (AMSB). FUJI is a size-flexible NEAR BREEDER even not using continuous chemical processing and core-graphite exchange, and AMSB is based on a single-fluid molten-salt target/blanket concept, the technological development of which is easy and simple except for the high-current proton accelerator. THORIMS-NES has many advantages, and here the issues of safety, nuclear-proliferation and social/philosophical acceptance is mostly explained. In practice, the shift to THORIMS-NES from the present U-Pu cycle era will be smoothly implemented by converting Pu and TRU in weapons and spent-fuels into molten fluoride salt by a drying process (such as the Russian FREGATE project) which was established by the French, Russians and Czechs. Pilot plant "mini FUJI", 7MW(e) might be commissioned after 7 years depending on the result of successful 4 years operation of MSRE in ORNL, and Small Demonstration Reactor "FUJI-Pu", 150MW(e) can probably be in operation 12 years from now utilizing the world ability of Na-Reactor Technology. Depending on such MSR-technology development, AMSB-Pu might be able to industrialize 20 years from now.

1. INTRODUCTION

The world is facing several serious crises not only from nuclear weapon-material but also from poverty, population explosion and environmental problems. To solve such issues in the next century the world needs huge energy supplies and it seems that nuclear fission energy is the most promising solution if the following issues are to be solved:

(a) safety
(b) radio-waste
(c) anti-nuclear proliferation and terrorism, and
(d) public/institutional acceptance and economy in the global application.

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* 1997 meeting.

Such an aim will not be achieved by minor modification of past technologies but should be expected to depend only on the principally new and ambitious fuel concepts. And it will be a semi-final attempt in the nuclear energy industry because the major energy technology at the end of the next century will be required to be non-heat-emission types such as solar energy.

2. GLOBAL ENERGY STRATEGY IN THE NEXT CENTURY

The 21st century will be a transient period from the fossil fuel age to the solar age through nuclear energy, as the global and especially the local climate could not accommodate the excess heat emission several times more than the present artificial heat generation. Therefore the heat-emission type energy technologies (even nuclear fusion or satellite electric-generation) will not be utilized as major ones in the 22nd century.

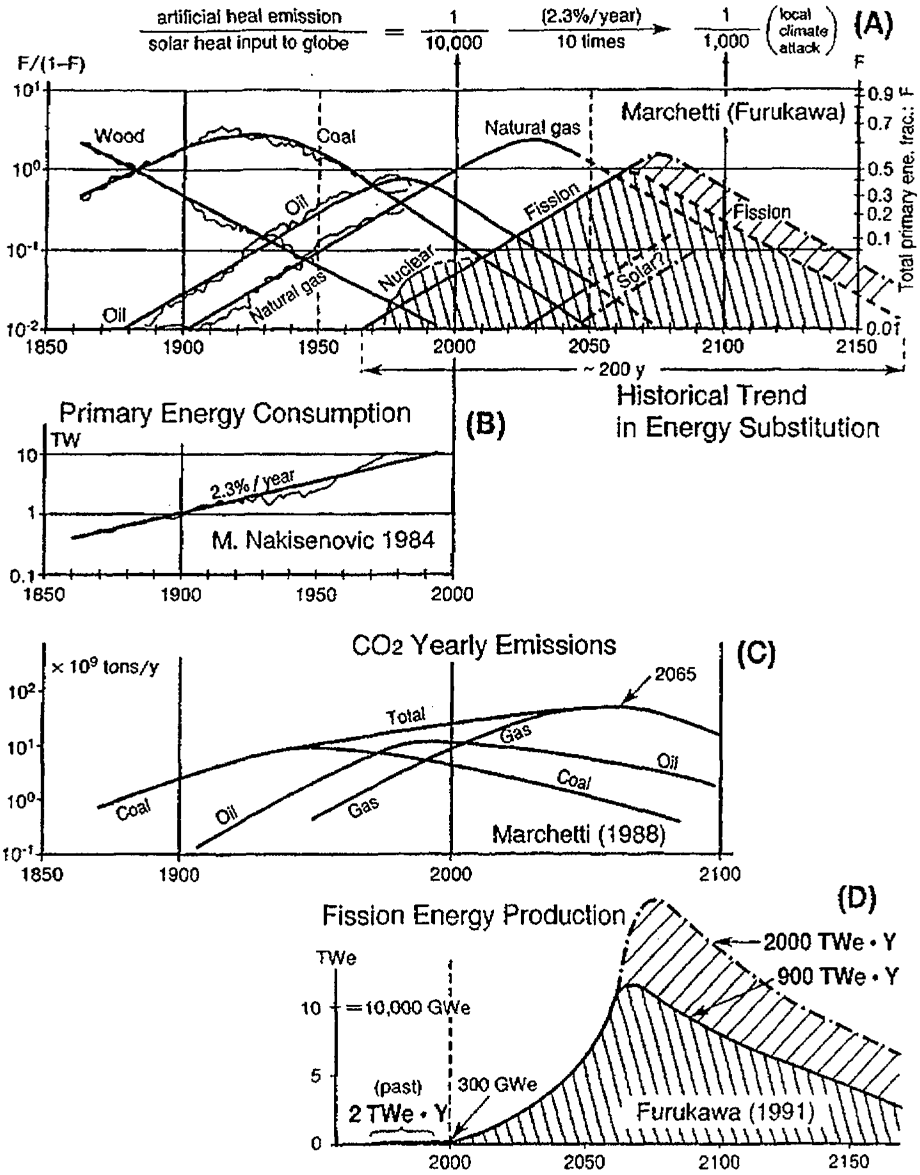

Figure 1. Global Future Energy Prediction. (A) is an extension of Marchett's estimate of historical trend in energy substitution; (B) growth-rate of world primary energy consumption. The predictions of © CO_2 yearly emission from fossil fuels, and (D) nuclear fission-energy production base on (A) and 2.3% annual growth-rate of world energy.

Such advanced prediction will be understood from the illustrations in Figure 1, basically depending on and extending the Marchetti's prediction on the future energy [1,2,3]. If we tentatively accept the global energy growth rate of 2.3% as in the past, the necessary fission energy will be "1000-2000" TW(e) per year in the next century. This is "500-1000" times larger than the past (peaceful) fission energy production of only "2" TW(e) per year (Figure 1(D)). (In here we have to recognize that even such huge nuclear energy will not be enough to solve the CO_2 Greenhouse effect as shown in Figure 1(C)[1]).

It will not be achieved by the present U-Pu solid-fuel cycle system such as lWR and LNFBR due to several difficulties connected with (a) safety [including severe accidents], (b) radio-wastes [including production of trans-uranium [TRU] elements, (c) nuclear-proliferation and -terrorism [including the plutonium-elimination issue], and (d) public and institutional acceptance related with the technological simplicity, flexibility and economy in the global applications.

A "nuclear energy system" should be a "NUCLEAR CHEMICAL REACTION ENGINEERING FACILITY" and essentially a "CHEMICAL PLANT'. Following that, a more rational nuclear energy system should be developed fully, re-examining all scientific/engineering efforts devoted in this century.

First of all, the "FISSION BREEDING POWER STATION" concept such as LMFBR and even MSBR [Molten-Salt Breeder Reactor] proposed by ORNL will not be practical due to (1) the complexity in structure and operation/maintenance (2) the weak breeding performance, and (3) non flexibility in power size [2]. As a new measure a simple rational thorium-molten salt breeding fuel-cycle system, named "Thorium Molten-Salt Nuclear Energy Synergetics [THORIMS-NES]" has been proposed [4,2], which might realize a rational New Nuclear Energy Era in 20-30 years.

3. NEW PHILOSOPHY: 'THORIUM MOLTEN SALT NUCLEAR ENERGY SYNERGETICS" (THORIMS-NES)

Our proposal, THORIMS-NES, depends on the following three principles [4,2]:

(I) Thorium utilization: Natural thorium has only one isotope, ^{232}Th, which can be converted into the fissile ^{233}U in a similar manner as ^{239}Pu converted from ^{238} U. ^{233}U is suitable for thermal reactors and produces only negligible TRU, but 233U fuel is accompanied with strong gamma activity requiring a fluid type fuel.

(II) Application of molten-fluoride fuel technology: The molten salt ^{7}LiF-BeF_2 (Flibe-named by OPRNL) is the significantly low thermal-neutron cross-section material and the best solvent of fissile and fertile materials. This liquid is multi-functional not only as nuclear reaction medium useful for fuel, target or blanket, but also as heat-transfer and chemical processing mediums, which was verified by ORNL [5].

(III) Separation of fissile-producing breeders (process plants-AMSB: Accelerator Molten-Salt Breeder) and power generating fission-reactors (utility facilities-MSR: Molten-Salt reactor): It will be essential for the global establishment of breeding-cycle all over the world. It should be recognized that the doubling time of fission industry growth needs 10 years as shown in Figure 1(D)[2].

This system is practically composed of simple power stations MSR named FUJI-series, fissile producers AMSB, and batch-type process-plants establishing a Symbiotic Thorium Breeding Fuel Cycle System [THORIMS-NES], which successfully presented a high public acceptance [Chap.7].

MSR: FUJI (as example): 155 MW(e) small fuel self-sustaining MSR: "FUJI-II", 7MW(e)

Pilot plant MSR: "mini FUJI-II', 1Gwe fuel-self-sustaining MSR: "super FUJI" [4,6]. FUJI-II will have fuel self-sustaining (near-breeder) characteristics even in small size, without core-graphite exchange and continuous fuel processing, which needs a huge R&D effort and investment, except the removal of Kr, Xe and T. The reactor is filled only with fuel-salt (ca. 10% vol) and graphite (ca.90% vol), which does not need to be exchanged during reactor life.

AMSB: The basic idea of AMSB was invented in 1980 depending on the "single-fluid type Molten-Salt target/blanket concept"[7], which is significantly simple and practical in structure. The target/blanket vessel is a simple pot of 4.5m in diameter and 7m in depth. A proton beam will be injected in off-center position of molten-salt vortex. Therefore, several serious technological problems related with (I) material compatibility and radiation-damage, (ii) heat-removal, (iii) spallation chemistry, and (iv) target shuffling (uniform continuous reaction) are solved by this design concept, except the proton-beam injection-port engineering which might be solved by the real beam test increasing intensity step by step and applying the gas curtain technology for example.

Technological rationality of THORIMS-NES: THORIMS-NES is a huge industry producing 1000-2000 TW(e) per year. In the development of this system, the following simple and rational nature of MSR technology should be recognized [2]:

> [A] no radiation damage in molten salt fuel and target/blanket, - chemical enert and stable glass forming
> [B] simple chemistry - highly predictable physico-chemical behaviors of molten salts - low R & D cost
> [C] simplicity in reactor design principle/configuration - commercialize from "small power stations"
> [D] widespread applicability of Na-FBR Technology results, hugely invested in the past, with the advantages of MSR Technology on the chemical enert, and low thermal shock.

These facts will guarantee the realization of THORIMS-NES in less than 20 years by very low R&D cost. Already ORNL has demonstrated an excellent 4 years operation of the experimental MSR named "MSRE" IN 1965-69[5]. The establishment of FUJI-II will b easily achieved in 12 years. AMSB will be developed in 15-20 years delaying a little, but it is enough because some difficulty to "initial ^{233}U fuel" can be solved by the following approach:
[F] easier commercialization by utilizing/eliminating commercial and weapon-head Pu [Chap.4].

4. PRACTICAL STRATEGY TO REALIZE TH-ENERGY ERA BY THORIMS-NES

Now the smooth and practical shift to Th-cycle: THORIMS-NES ERA from U-Pu Cycle ERA is the most important issue. After the termination of the Cold World War, this might be implemented easier that before including the effective incineration/elimination of weapon materials and Pu, although such work should be performed inside a safeguarded area. Some detailed examination of this strategy has been reported in IAEA Tech.Comm.Meeting, Vienna, 1995[8] and others [9]. Here it will be briefly explained.

ORNL already demonstrated by means of their experimental reactor. MSRE that MSR can use any kind of fissile materials [10]. The only problem will be the solubility limit of Pu and TRU fluorides.

The complete elimination of Pu at present and in the future will be really established economically if we use the following strategy:

(1) D-plan: Pu (and trans-U elements [TRU] separation straightway in the form of molten fluorides by Dry-process from the spend solid fuels accumulating in the world. The technological basis has been examined by France, Russia and the Czech Republic and realized as the Russian FREGATE-project [11]. Here we need not reproduce any solid fuels.

(2) F-plan: Pu-burning and ^{233}U production by Fission MSR [FUJI-Pu], as explained already in Sec.4.1.

(3) A-plan: The same as the above (2) by AMSB-Pu, with F-plan, even delaying about 5-10 years.

Plutonium and TRU can effectively be transmuted by AMSB-Pu, producing ^{233}U in parallel in which the production ratio of ^{233}U to transmuted plutonium is much higher than the case of FUJIO-Pu [8].

Table I. The standard performance of FUJI-Pu [per 1 GE(e)] and AMSB-Pu [per 1 GeV 300 mA]

	Pu inventory	^{233}U inventory	Pu burnup/a	^{233}U production	Electr. output
FUJI-Pu	3t		0.86t	0.7t	1 GW(e)
FUJI-II		2t		self-sustain	1 GW(e)
AMSB-Pu lg	5t	0t	0.35	0.7t	-0.15 GW(e)
AMSB-PU hg	5t	5t	0.52	0.9t	1 GW(e)

However, the development of AMSB-Pu will be delayed than FUJI-Pu due to the large-current accelerator development and proton injection port engineering, although ASMB has significant technological advantages in the issues of radiation-damage, heat removal and reactor-chemistry.

U-Pu cycle system could not realize the energy production predicted in Figure 1(D) owing to the huge amount and steep increase. However, THORIMS-NES will be able to realize the following several scenario applying the above D-, F- and A-plans. Here, one of the simplest examples has been shown in Figure 2.

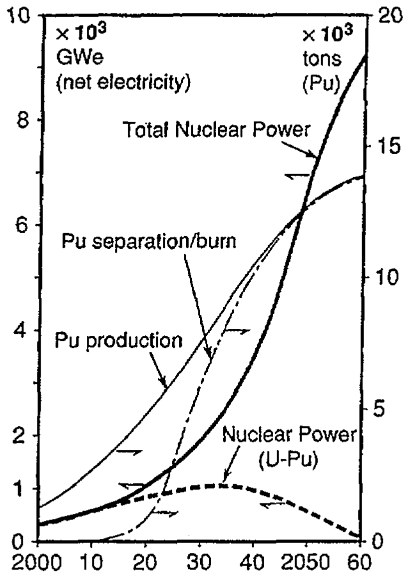

Figure 2. A scenario for THORIMS-NES deployment using plutonium incineration in the next century.

Tentatively the system size of U-Pu cycle power stations will be assumed as 4 times larger in maximum than the present. Even so low this will still produce more than 10^4 t plutonium (assuming 300KgPuk/GW(e) Y net) until 2050, which will be separated by Purex or D-plan process accompanying TRU in all the more proliferation-resistant mode, because a simple storage of spent-fuels will be a non real solution. Plutonium (TRU) disposition could be started from 2010 by F-plan, and from 2020 by A-plan in parallel. The former activity will become 200 Gwe in maximum scale about 2030, burning about 2600 ton plutonium (TRU) or more. The latter will become 800 facilities in peak about 2040, burning about 10,000 ton plutonium (TRU) or more. The duty of FUJI-Pu will be finished until 2040. Now it can openly operate as proper $TH^{233}U$ power stations till the end of reactor life.

The technical development of AMSB-Pu will be significant in 2020 and 2040. The initial AMSB-Pu will be in lower grade (1g) not producing any outer electricity. Afterward the next high grade (hg) version will produce electricity improving in performance by near critical condition till the production of 1 or 2 GW(e)/facility [3].

After the middle of 2040 decade in which plutonium would be almost eliminated AMSB-Pu should be gradually dismantled, recovering ^{233}U fissile, which is useful to initiate FUJI power stations more. Therefore the main leading role of AMSB will be in the period of 30-40 years although afterward it will be continuously useful for radio-waste incineration as a flexible nuclear reaction facility [Figure1].

5. SIGNIFICANT ADVANTAGE IN SAFETY ISSUE

5.1 Basic Characteristics of MSR Safety

MSR, FUJI (and AMSB in general) is a significantly safe reactor, and has essentially "NO SEVERE ACCIDENTS". The most important safety performances are coming from the following factors:

(1) The primary and secondary systems are lower pressure than 5 bars, and do not have the danger of accidents due to high pressure such a system destruction or salt leakage.

(2) The fuel and coolant salts are chemically inert, and no firing or explosive with air or water.

(3) The boiling point of fuel salt is about 1670K or more, much higher than the operation temperature 973K. Therefore the pressure of primary system cannot increase.
(4) The fuel salt will be able to become just critical when it coexists with the graphite moderator. Therefore, leaked fuel salt will not induce any criticality accident. {EPI-thermal-type MSR is not the same.]
(5) MSR has a large prompt negative temperature-coefficient of fuel-salt. The temperature-coefficient of graphite is slightly positive, but controllable due to the slow temperature-increase depending on its high heat capacity.
(6) The delayed-neutron fraction in ^{233}U fission is smaller than that in ^{235}U, and half of the delayed-neutrons is generated outside the core. However, it is controllable owing to the longer neutron-life, and large negative prompt temperature-coefficient of fuel salt.
(7) As the fuel composition can be made up anytime if necessary, the excess reactivity and required control rod reactivity are sufficiently small, and the reactivity shift by control-rods is small.
(8) Gaseous fission such as Kr.Xe and T are continuously removed from fuel-salt, minimizing their leakage in accidents and in the chemical processing.

5.2. Basic Concept Securing the MSR Safety

For the confinement of radioactivity all reactor should have the following three safety functions:

[a] Reactor Shutdown Function: to stop (shut-down) the fission and to terminate the energy generation.
[b] Cooling Function of the Reactor: to keep the integrity of the fuel by providing enough cooling, and to prevent the release of radioactivity.
[c] Confinement Function of Radioactive Materials at Accident: to limit the release to the environment of radioactivity in the case of big accidents.

Besides the above, the concept of "Multiple Defence (Defence in Depth)" is adopted to assure the higher safety of the facility, taking in the following three different levels:

Level 1: Prevention of the abnormal situation when the reactor is operating: the reliability of equipment is raised sufficiently in design, manufacturing and maintenance.
Level 2: Prevention of the expansion of the abnormal situation: by the detection of abnormality in an early stage, by the plant inherent safety and by the reactor shut-down equipment.
Level 3: Prevention of the large release of radioactive materials: by setting up containment and ECCS. The multiple defence concept in MSR should be the same as LWR, and will be not touched more.

The above three safety functions [a], [b] and [c] in MSR will be explained as follows [12].

[a] Reactor Shutdown Function (Table II]:

All reactors should have inherent safety, which is achieved by suppression of power change by designing the reactor with a negative power coefficient. Because the temperature coefficient of fuel-salt is prompt negative and large, this condition is satisfied in MSR.

Control rods are also used for a rapid shutdown, and the fuel-salt drain system is also able to be used as another reactor shutdown function. Because the excess reactivity is small, the number of control-rods is few and the diameter is large. The reliability will be high. The drain system is always necessary and effective on the pipe rupture accident. Since the fuel-salt falls to the drain tank by gravity through the freeze valve with a simple mechanism, its reliability is high. Although the freeze-valve operation may be slow, rapid response needs not due to no re-criticality.

Table II. Comparison of Reactor Shutdown Functions

demand function	LWR	MSR	merit on MSR
High Speed Shutdown System (Scram)	Control Rod	Control Rod	enough with small numbers
Second Shutdown System	Boric Acid Injection System	Fuel-Salt Drain System	no re-crificali1y in Drain Tank
Third Shutdown System		Fuel-Salt Composition Adjusting System	also used for makeup of Thorium Component

As a third measure, the adjustment of fuel composition using fuel-salt controlling system is possible to shutdown the reactor. One approach will be the Th addition, which is necessary to make up fuel-salt in any MSR, and again a slow action of this system does not cause any problem.

[b] Cooling Function of the Reactor [Table III].

In MSR, the possibility of piping rupture is very low due to the low pressure, and the ECCS will not need the same as FBR (Monju). It is possible to deal with the drain system, even if a piping rupture causes the fuel salt loss. Of course the decay heat removal system is necessary for the drain system.

Table III. Comparison of cooling functions of core in emergency

demand function	LWR	MSR	remark on MSR
Cooling Water make-up	ECCS	unnecessary	unnecessary (Drain System can be used as backup)
heat removal	Decay Heat Removal System	Decay Heat Removal System	for severe accident countermeasure

Table IV. Comparison of radioactive materials confinement functions

wall number	LWR	MSR	remark on MSR
1	Pellet	none (Liquid Fuel)	no LOCA, Gaseous Fission Products are removed always
2	Cladding	none (Liquid Fuel)	same as above
3	Pressure Vessel, Pipes	Reactor Vessel, Pipes	very low pressure
4	Containment	High Temperature Confinement	no Steam generation, no Flammable Gas generation
5	Reactor Building	Reactor Building	same as LWR

The MSR may have a capability of natural circulation when all pumps stop, because the pressure loss in the core is small. Detailed evaluation is necessary in the future. When natural circulation cannot be expected, or when a turbine system is isolated and the cooling by the secondary loop is impossible, the decay-heat removal system is necessary. As a final heat sink, the decay heat removal system by a static air cooler as in FBR is preferable to endure a long term severe accident, such as all AC power supply loos ("station black out") accident.

(c) Confinement Function of Radioactive Materials at Accident (Table IV]:

For this purpose, five barriers are applied in LWR. The first two barriers do not exist in MSR because MSR uses fluid fuel. The chance of radiation exposure by gaseous fission products (FP) is smaller due to their continuous removal from fuel-salt, and the danger of piping rupture is also very low. Therefore it is thought that the MSR safety is better than LWR.

The primary system of MSR is enclosed in a "high temperature confinement" and the entire reactor system is covered in the "containment" which is a reactor building itself. These arrangements are basically equal to the LWR. Since there is no water and no flammable gas generation, the MSR safety is excellent due to very few events which can threaten the integrity of containment.

5.3 Design Basis Accidents (DBAs)

Regarding the safety of MSR, accidents are categorized into two areas. The first is the so called DBAs (Design Basis Accidents) and the second is the severe accident which exceeds DBA.

DBAs are categorized into two events (A) initiated by dynamic equipment and (B) by static equipment. (A) is divided into two typical accidents (A1) and (A2), and (B) is divided into five (B1)~(B5) as shown in the following (2):

(A1) Fuel salt Flow Decrease Accident: In MSR, there is judgement that "the reactor is safe for the stop of all primary pumps, if an appropriate scram system is designed" [13]. One example of a scram system is a control rod drive located at the upper part of the core and control rods which will be inserted into the core by gravity, when an accident occurs.

(A2) Reactivity Insertion Accident (RIA): Although the added reactivity is small there is a possibility that the accident results are severe, because the effective β (= delayed neutron fraction) of MSR is only 0.1% ΔK(=1/5 of LWR). The reason is that β of ^{233}U is 0.26% which is about half of ^{235}U, and the half of β is lost when the fuel-salt flows outside the core.

Regarding the addition of a reactivity, mis-withdrawal of control-rod does not happen, because safety control-rods are always withdrawn when the reactor is in operation. Regarding the power increase by mis-insertion of the graphite control rod, it is small owing to the very small rod reactivity.

It might be a cold loop start up accident that the largest reactivity is added to the reactor as a reactivity insertion accident. It is an accident which can have a positive temperature reactivity coefficient when the stopped pump starts, and the fuel salt of relatively low temperature enters the core and then the absorption of neutrons by the Doppler effect becomes small. Since the reactivity insertion of 3 dollars (= 0.3% ΔK) is due to a 100°C decrease of the fuel salt temperature, this event is really a reactivity insertion accident. However, this event terminates by scram with the negative temperature coefficient of fuel-salt, although the fuel-salt temperature increases to some extent. In addition, since the prompt neutron lifetime of MSR is about 10 times longer than LWR, the power increase is mitigated for the prompt accidents.

(B1) Fuel Salt Loss Accident: The possibility of piping rupture is very low due to the low pressure and no steam existence. Meanwhile, it is possible to collect the lost fuel-salt to the drain tank (para.5.4].
(B2) Heat-transfer Piping Rupture Accident of HX (Heat Exchanger): In this case, secondary coolant salt enters the core side, because the secondary side contains higher pressure than the primary side. The boron content of coolant salt mixes with the fuel salt and the reactor stops.

(B3) Heat transfer Piping Rupture Accident of SG (Steam generator): In this case, it is necessary to evaluate the influence, because the steam of 200-250 bars flows into the secondary coolant-salt. However it is said that the molten salt does not cause a chemical explosion unlike Na, and therefore any serious influences on the primary system will not be induced.
(B4) Disruptive Accident in Off-gas System: Since MSR always removes gaseous FP from the primary system, off-gas treating facility accumulates a large amount of radioactive gas. Moreover, the cover-gas system of secondary loop accumulates Tritium generated from Li in fuel-salt, although T is transformed to water and easily controllable. Anyway, since it is a static facility unlike the main body of the reactor, correspondence is not difficult. Of course, countermeasures against the disruptive accident of off-gas systems are necessary.
(B5) Mis-operation of Fuel-salt Adjustment Equipment: This equipment is necessary in MSR to make up the salt components. It is necessary to design it so that a large amount of fissile materials is not inserted by this equipment. Since the inventory in this equipment is very small compared to that of cores, rapid reactivity insertion does not happen.

5.4 Severe Accidents

Based on the above review on DBAs, the following three main events are examined [12]:
(1) *Fuel-salt Flow Decrease Accident*: As a severe accident of MSR, it is necessary to assume *Scram Failure*, and *All Primary - and Secondary-Loop Pumps Stop*. Since ΔT (temperature increase between core fuel-salt inlet and outlet) is proportional to P/W (Power/Flow), temperature increase (reactivity decrease) by W becoming 1/10 from the related value and temperature decrease (reactivity increase) by P becoming 1/10 from the related value will balance.

By the way, if the speed of the pump of MSR is changed, it is possible to change the power output using the above phenomena, and this is one of the advantages of MSR.

As explained above, when the flow decreases, reactivity decreases by temperature rise, but a small positive reactivity is inserted by the increase of delayed-neutrons. This is because the delayed-neutron precursors, taken away outside the core, stay in the core.

Shimazu concluded by a quantitative analysis [13] that "The flow decreases to a power level of about 10% after 10 seconds, according to the analysis assuming that the flow becomes zero when all pumps stop. The exist temperature rises from 973K to 1170K".

In an actual situation, it is necessary to remove the decay heat. If both the primary and secondary loops circulate naturally, the decay heat of the core can be exhausted outside the rector. When natural circulation is impossible, the decay-heat removal system is actuated (para.5.2 [b]). Therefore it is safe enough even if both the primary loop pumps and the secondary loop pumps stop in a severe accident case.

There is a *Flow-Path Plugging* with debris, which is one of the other scenarios of the flow reduction. This scenario is reviewed relating with MSBR [5] and it says, "If the fuel salt temperature reaches the boiling point, there may b a problem caused by a positive void coefficient. But there are hundreds of channels in a core, and even if 100% void happens at 20 channels simultaneously, void reactivity is only 1$. In addition there is an effect that the fuel itself disappears, and it is unlikely to become a problem. However, further examination is necessary".

(2) *Reactivity Insertion Accident*: It might be a *Cold Loop Start-up Accident* that the largest reactivity insertion is forecast as a reactivity insertion accident. Since the temperature coefficient of the fuel salt is about $-3x10^{-5}$ $\Delta K/K/^{o}C$, the inserted reactivity is about 3$ (0.3% ΔK), because the fuel salt temperature decreases about 100 ^{o}C.

This scenario is calculated on MSBR by Shimazu [14] and it says, "At zero-power or full-power condition, 3$ reactivity insertion with scram failure assumption, the fuel-salt negative temperature coefficient mitigates the event, and the highest fuel-salt temperature is 1473 K. This temperature is lower than the melting point of Hastelloy N (1640 K), assuming that the temperature of the core vessel is the same as the temperature of the fuel-salt." Therefore the MSR has enough safety for the reactivity insertion accident.

(3) *Fuel Salt Loss Accident*: Basically, the *Fuel Salt Loss Accident* happens only as a severe accident. As a result of any pipe rupture accidents in MSR it is possible to terminate the accident if the system is designed to collect the lost fuel-salt into the drain-tank. Also it is necessary to design the drain tank system using natural heat radiation in order to endure a long-term cooling of the decay-heat. Since the fuel-salt becomes a solid (a stable glass) below the melting point at a final stage, it is not necessary to consider a so-called China Syndrome. If the drain system with natural heat radiation is designed, the integrity of containment is secured. Therefore, in MSR, it is possible to prevent the worst severe accident scenario such as the containment failure = China Syndrome = a large amount of radioactivity release.

Moreover, the *Re-Criticality Accident* does not occur. This depends on the fact that concentration of fissile material in the fuel-salt is low, and the fuel salt does not become critical without an appropriate amount of moderator such as graphite.

In addition, since the gaseous fission products are always collected in MSR, the amount of radioactivity release is small, even if there is a radioactivity release accident.

6. ADVANTAGE IN NUCLEAR-PROLIFERATION ISSUE

THORIMS-NES brings high proliferation-resistant nuclear fuel cycles to the world through covering fissile material in the near future from Pu to ^{233}U. Advancements in proliferation-resistance will be observed in the following three view points [15]:

(1) Macroscopic View in Global Fuel Cycles: plutonium in spent fuels of various thermal; reactors are steadily increasing in the world. Especially vast amounts of them are expected in developing countries in the near future through the promotion of nuclear power generation, mostly with LWRs.

Plutonium brings proliferation risks even when it remains in spent fuels. They should be subject to more stringent safeguards compared to new fuel made from low enriched uranium. But there is always the risk of theft or diversion, especially in the case of solid spend fuel, which is easier to handle than liquids or solidified fuel-salt of MSRs. Even if spend LWR fuels would be disposed in a deep geological stratum, they might form a potential future plutonium -mine because radioactivity of fission product decays out in a long time.

However, when spent LWR fuels are reprocessed from the reasons of waste volume reduction or the issue of energy resources - that will be very likely - proliferation risks will further increase unless we have a good scheme for utilizing separated plutonium. When the plutonium is used again in LWRs, i.e. LWR-MOX cycle the problem will not be much changed from the usual LWR cycle and remain unsolved. On the other side, if the plutonium is used in FBR cycle it will bring more issues, to be described in the following paragraph (2).

So, thorium fuel cycle development through plutonium incineration by THORIMS-NES is the best scheme we have for this purpose, since it actively reduces and simultaneously suppresses new production of spent fuels containing plutonium.

Plutonium utilization in MSR which brings power generation and converted ^{233}U simultaneously might be the only possible way to let effective use and nonproliferation of nuclear materials be compatible, because it has the following advantage over FBR fuel cycle. Therefore THORIMS-NES would be able to make a great macroscopic contribution to global fuel cycles.

(2) Plutonium vs. ^{233}U (FBR vs MSR): Significant quantity (SQ) in nuclear safeguards is not so much different between plutonium (8kg as element-total) and ^{233}U (8 kg in isotope) but diversion resistance will be significantly larger in ^{233}U.

One core fuel assembly for FBR usually contains about 1 SQ of plutonium and it is rather small and easy to handle and conceal for diversion or theft. Blanket fuel assembly for FBR has lower plutonium concentration than core assembly, and several blanket assemblies are required to get 1 SQ of plutonium. But their plutonium is very near to the weapon grade and attractive to the potential divertor. On the other hand, fissile material concentration in MSR fuel is low as is described in (3), and it is difficult to get 1 SQ because of the required large amount (1-2 tonnes) and the inconvenient form for theft. Moreover, plutonium in MSR-Pu is usually too old for weapon use and ^{233}U accompanies strong radiation as described below.

^{233}U usually contains more than 500 ppm ^{233}U and its daughter nuclides, some of which emit strong high energy (208I1 2.6 MeV) gamma rays. They bring lethal doses of 1-2 Sv/hr at 50 cm distance from 1 SQ (8 Kg) ^{233}U. To shield it more than 20 cm thick lead is necessary, which emit strong high energy (^{208}I1 2.6 MeV) gamma rays. They bring a lethal dose of 1-2 Sv/hr at 50 cm distance from 1 SQ (8 Kg) ^{233}U. To shield it more than 20 cm thick lead is necessary, which in fact makes it impossible to steal and fabricate nuclear explosives.

To procure pure ^{233}U it is necessary to separate its precursor ^{233}Pa. However the separation of dilute ^{233}Pa is chemically not easy work, and its half-life lasts only 27 days.

^{233}U can easily be denatured by adding ^{238}U if required. Even in this case ^{238}U concentration in MSR fuel is maintained fairly low, about 1/10 of the main fertile material thorium, because of low concentration of ^{233}U. This prevents not only to spoil the nuclear characteristics but also to produce Pu and higher nuclides [Am, Cm etc.], which have the potential to easily become weapon material. This liberation from TRU elements is the great merit of Th- ^{233}U fuel cycle, and the U-Pu fuel cycle never gets out of this yoke.

FBR fuels must be recycled in fairly short periods to retain their breeding power at a practical level. So annual throughput of plutonium in FBR fuel cycle will become very large and bring significant safeguards and transportation problems. Required plutonium inventory in one FBR (1 GW(e)) is several tonnes of plutonium, for example, 1% of them becomes several SQ. Hold-up of the order of 1% will be apt to occur.

The situation in MSR/THORIMS-NES is much easier, because the ^{233}U.inventory in MSR is about ¼ of plutonium in FBR and it will become effectively fuel self-sustaining near breeder. These will result in few transportation occasions and little fissile material throughput.

(3) Microscopic View in reactor Site: Fissile material concentration in MSR fuel is low in both cases of MSR-Pu and MSR-^{233}U, and the typical concentration will be about 1 wt% of them. Therefore the fuel salt containing 1 SQ (8 kg) of plutonium or ^{233}U weighs 800 Kg with the volume of about 250 litres. In practice these fissiles will be dirty and need larger amounts of salts. This makes theft effectively impossible.

MSR does not have large excess reactivity. So even when a diversion by the operator is made, the fact can easily be detected b the inspector. This will be effective to deter theft. MSR has a further merit in that it has only a little additive fuel and spent fuel at its site.

High gamma dose level of ^{233}U cycle fuel serves also to provide easy detection of the irregular tranfers in the normal fuel handling route. In case of FBR there is a proposal to intentionally add radioactive TRUs into plutonium. But in the case of ^{233}U the radioactivity accompanies naturally, and it brings no obstacle in nuclear characteristics of the reactor.

Reprocessing and re-preparation of MSR liquid fuel is simpler and easier than those of FBR solid fuel. This will reflect the possible difference of theft and diversion between the two reactor types. Transportation - the vulnerable point in fuel cycle - can also be much reduced in MSR, because it is principally a self-sustaining "*Near Breeder*" and it usually has on-site processing and re-preparation of the fuel. These advantages can similarly be held in he case of AMSB (accelerator molten salt fissile producer). AMSB and the fuel-salt processing facilities will be non-utility/process plants in essence, and will be accommodated inside Regional Centers heavily safeguarded. This separation plan of the breeding facilities from the very little consuming power stations is a good management scheme of nuclear materials.

To summarize the above, it should be strongly recommended to convert plutonium to "the hardest and least desirable fissile material for weapon - ^{233}U through MSR-Pu and gradually to shift to MSR- ^{233}U fuel cycle on a global scale. The effectuation of the Comprehensive Test Ban treaty makes it impossible to make the explosive test for the ^{233}U bomb development. This condition also suggests a more safe world using ^{233}U than plutonium.

7. IMPROVEMENT IN SOCIAL ACCEPTANCE

The nuclear energy community is suffering serious criticisms from the public not only on safety, radio waste and nuclear proliferation issues, but also inflexibility/instability in public relations. This depends mostly on the influence of the past *Cold world war*. Now a new Nuclear Era should be reconstructed following the recommendation of the late David E. Lilienthal encouraging "a revival of its positive, affirmative fighting spirit" of scientists [16].

For such purpose the THORIMS-NES will be able to contribute as shown in the following lists:

Socio-Philosophical Advantages of Thorium Molten-Salt Nuclear-Energy Synergetic System [THORIMS-NES]

Notation:

(Q): Old Development Philosophy based on *Current Nuclear-Energy* technology approach
[A]: New Development Philosophy based on THORIMS-NES approach

(Q1) Introduction of "Controlled Society" derived from "Controlled Management of Nuclear Materials.
[A1] Normal Society protected by **enhanced resistance to Nuclear Proliferation/Terrorism** depending on Th-U Fuel Cycle: elimination of Pu & Trans-U elements, and intense 2.6 MeV gamma of ^{232}U.

(Q2) Huge Protection Work on **Radioactive Exposure**
[A2] Wide application of Remote Operation/Maintenance, Curtailed Maintenance, Handling and Processing of Fuels & Radio-Wastes based on Fluid-Fuelled Reactor: Molten-Salt Reactor.

(Q3) Comprehensive Restraint to achieve **"Material Quality-Control"** and "Operation/Controllability" for Hazard-Protection.
[A3] Fundamental "Reactor Safety" enhancement such as **"No Severe Accident"**: no core melt down, no re-criticality, restricted radio-activity release, and resistance to military attacks or sabotage.

(Q4) Burden of Future Generation: Radio-Waste Management for centuries and millennia.
[A4] No Production of Pu, Am, Cm [Trans-U elements] limited Dilution of High-level Radio-Waste and minimized Amount of Low-Level Radio-Waste due to reduced Maintenance/Process Works [cf.[17]).

(Q5) Large Efforts and Emphasis on **R&D** to facilitate Political Control, Monopoly, Power Centralization.
[A5] "Short Term", "Low Cost" and "Simple (few items, esp. in fuel development)" **R&D Program**, based on "Nuclear Chemical Engineering [liquid medium]" Principle of Nuclear Energy System.

(Q6) Big Complex Science: Non or Costly testing for elaborate **System Size and Sophistication.**

[A6] Simple, small and Testable [no Severe Accident] **Power Stations** owing to Separation of Power Reactors and Fissile-Producers, denying "Fission Breeder Power Reactor" concept.

(Q7) Compelled "Public Acceptance" from the side of Nuclear Energy Promoters.
Loss of Individuality and Persona Liberties, and **Human Estrangement.**
[A7] Return to Original **Scientific Spirit,** and should prepare a really safe, flexible and economical "PUBLIC INDUSTRY', depending on rational/practical Principle of Nuclear Energy Technology.

It will be optimistic, but we need such technology. And the THORIMS-NES concept is young and will have potential for further improvement. Therefore the above will be recognized as a promising target of our effort. We have to proceed for preparing the future "**Open Society**".

8. CONCLUSIONS

The biggest handicaps to the Th-MSR concepts originated by ORNL are the unbelievable excellence in the scientific and technological basis, not requiring significant money and personnel, and resulting in no accident during the MSRE project, 30 years ago. Although all their results had been published, it is not easy to obtain those.

Now we have to start improving he excellent ORNL results to the most suitable form in the next century. The most effective first measure will be the demonstration of integral MSR technology by the simple pilot-plant: 7MWe miniFUJI with a reactor-vessel size of 1.8 m diameter and 2.1 m high [4,6].

As a conclusion, the following final sentence in the last book, **"Atomic Energy: A New Start"**, by David E. Lilienthal [16], a notable American will be shown in the hope that our work might be useful as a trial reply to his sincere wish:"**What I have reflected upon and written about is not merely a new source of electrical energy, nor energy as an economic statistic. My theme has been our contemporary equivalent of the greatest of all moral and cultural concerns - fairness among men and the endless search for a pathway to peace."**

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